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DESIGN, FABRICATION, AND CALIBRATION OF A CRYOGENIC SEARCH-COIL ARRAY FOR HARMONIC ANALYSIS OF QUADRUPOLE MAGNETS*

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Abstract: A cryogenic search-coil array has been fabricated at LBL for harmonic error analysis of SSC model quadrupoles. It consists of three triplets of coils; the center-coil triplet is 10 cm long, and the end coil triplets are 70 cm long. Design objectives are a high bucking ratio for the dipole and quadrupole signals and utility at cryogenic operating currents (~6 kA) with sufficient sensitivity for use at room-temperature currents (~10 A). The design and fabrication are described. Individual coils are mechanically measured to ±5 μm, and their magnetic areas measured to 0.05%. A computer program has been developed to predict the quadrupole and dipole bucking ratios from the mechanical and magnetic measurements. The calibration procedure and accuracy of the array are specified. Results of measurements of SSC model quadrupoles are presented.

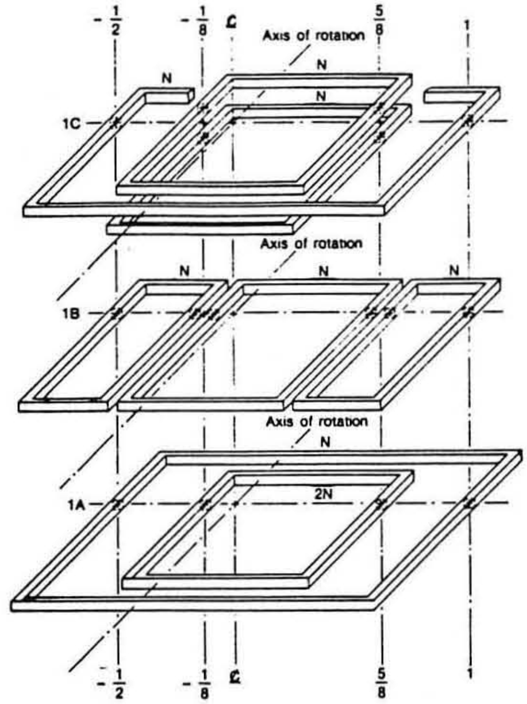
Introduction

The search-coil array was designed for making strength and harmonic error analysis measurements of 1-m-long SSC model quadrupoles.[1] Design objectives included an accuracy of 0.1% for the strength, resolution of 0.01 units (1 unit is 1 part in 10,000 of the fundamental strength), cryogenic measurements at 6 kA and warm (room-temperature) measurements at 10 A, i.e., a dynamic range greater than 10^9. Room-temperature measurements are performed at currents of less than 20 A to limit magnet heating. Cold-bore measurements require the assembly to withstand many temperature cycles from below 4 K to room temperature without mechanical deformation. The need for integral measurements, measurements representative of the uniform central section, and measurements of the end sections of quadrupoles required three separate search-coil sets on one assembly.

The search coil has been used both for warm and cryogenic measurements. A bucking ratio of greater than 250 has been attained for the important central search-coil set.

Electrical Design

The electrical design requirements included a high bucking ratio (i.e., low sensitivity) for the dipole and quadrupole terms when the error harmonics are measured. Since the search-coil array would be used at both room and cryogenic temperatures, bucking by resistive networks is complicated by the temperature coefficient of the resistivity of copper wire. Figure 1 shows the three search-coil configurations that were considered. All three designs feature radially (rather than azimuthally) distributed coil bundles, located at normalized radii of 1, 5/8, -1/8 and -1/2. The coils in designs 1a and 1c all have N turns, whereas the center coil of design 1b has 2N turns. The quadrupole strength is detected by using a single coil of a set, whereas harmonics are detected by configuring the coils in a set so that they are series opposing. Each of the designs has the ability to simultaneously buck out both the dipole and the quadrupole terms when measuring harmonics. Design 1a was not used since this design is



Quadrupole Search Coil Configurations

Figure 1. Coil bundle configuration considered for a quadrupole search-coil array.

only appropriate for making integral measurements--the ends of the search coils do not end at the same axial position. Design 1c was chosen because the widths of the coils are twice as wide as for design 1b, leading to easier fabrication and higher accuracy. The higher accuracy would also lead to a higher bucking ratio.

A high bucking ratio 1) allows the measurement of the error harmonics with much higher resolution, since the error harmonics are not superimposed upon a large quadrupole signal, and 2) reduces mixing of terms when the search coil is not perfectly centered.

Mechanical Design and Fabrication

Figure 2 is an exploded view of the search coil. The final assembly is essentially a solid piece of Nema G with embedded search-coil bundles. Much care was taken in the design and fabrication to reduce stresses that might produce mechanical deformations due to thermal cycling from room temperature to cryogenic temperatures.

The search coil body was laminated from 1/16-in.-thick cryogenic-grade Nema G-11; 3.75-cm-wide strips were cut from one sheet and numbered in sequence on one end. The lamination was laid up with the numbers alternating end to end and facing up and down to cancel out possible existing stresses in the sheet. The directions called for the sheet to be lightly sandblasted on each side and for both sides of each strip to be coated with a 50/50 mix of epoxy 826/Versamid 140. The layup was weighted/clamped uniformly on a surface table. The shaft consists of two equal halves, which were ground to a flatness and dimensional accu-

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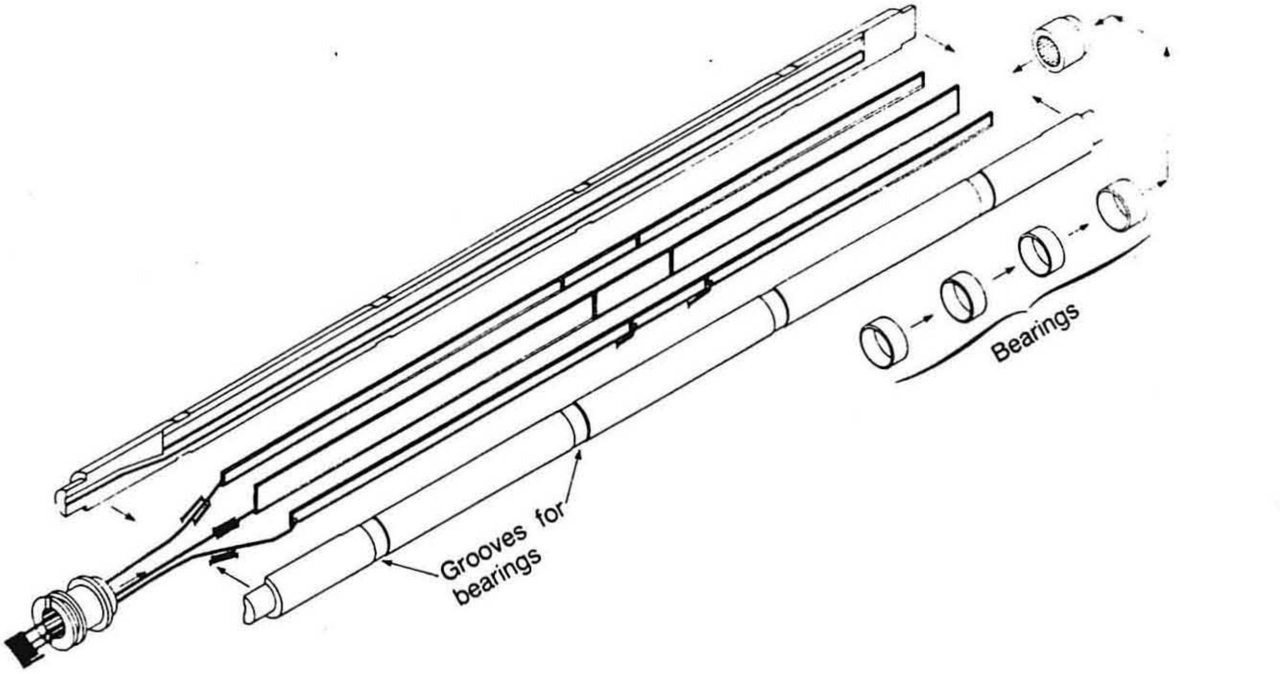

Figure 2. Exploded view of a quadrupole search-coil array.

racy of ±12.5 μm. A cavity was milled in each half to accept the three search-coil sets. The two halves were doweled and screwed together along with dummy coil sets for a spacer. The diameter was then machined to the required dimensions, the shaft disassembled, and the cavities referenced to the outside diameter at the location of the bearings. The offsets were marked on the shaft, and the shaft was reassembled. The shaft was mounted in a lathe with the bearing area next to the head stock, and the shaft was then positioned onto the center line of the cavities by means of dial indicators. The cut-out grooves for the bearings were then machined to the required diameter.

A dry layup was made with all the coils and wires in position to ensure there would be no problems in the final assembly. Each part was coated with the epoxy 826/Versamid 140 mixture and joined with dowel pins and machine screws. Excess epoxy was removed. It should be noted that the screw heads alternate from side to side to prevent warping of the assembly. The shaft assembly was weighted down on a surface table with a right-angle vertical stop in place and allowed to cure for over 72 hours at room temperature. The assembly was then vacuum potted with epoxy to ensure complete filling of all voids.

The shaft has four bearings axially spaced so as to minimize any bending. The bearings are made from Rulon LD (low deformity) and ride on two dimples, each 45° from the bottom center line, pressed into the bore tube with a special fixture. The dimples are approximately one inch long and of a height calculated to put the shaft axis exactly on the bore-tube axis.

Experience has shown that a burnished Rulon bearing sliding on a polished stainless-steel surface has far less friction than aluminum bronze on stainless and does not give the electronic glitches generated by the stick/slip motion associated with ball or roller bearings used on previous search coils.

The Rulon bearings were installed in the shaft grooves onto a coating of epoxy, and a clamp of the exact bearing diameter was bolted over each bearing to obtain the specified final bearing diameter. The nose piece and axial-positioning bearing were then epoxied into place, completing the assembly of the shaft.

The coil winding forms were produced by grinding the 1/16-in. Nema G-11 to 0.0500 in. ± 0.0002 in. The assembly requires one 10-cm-long coil triplet and two 70-cm-long coil triplets. An ~0.050-in.-square cross section for each coil bundle was obtained by winding 16 layers, 12 turns each, of 6-mil copper wire. The wire was Formvar insulated with a 0.2-mil Poly Bondex coating on top of the formvar. Each turn was tensioned to 75% of yield and placed, while being viewed under magnification, in a nesting configuration. The winding tooling was designed to provide a cavity for the wires that would produce the desired square cross section. The coils were wound and then cured to polymerize the Poly Bondex coating. After curing, the coils were measured with 1-μm resolution and 5-μm accuracy by an optical X-Y stage. These measurements were compared with the before-and-after winding dimensions and later correlated with the triplet coil array's magnetic measurements. Several test coils were produced and measured to achieve the dimension control necessary. This required careful adjustment of the winding cavity to compensate for the epoxy flow, nesting, and Nema G-11 stability. The widths of the final coils produced were accurate to within 15 μm over a length of 70 cm. This particular winding and fabrication technique, which has been used in the past, has been pushed to its limits for this coil.

Testing and Verification

Overview

The primary objective of the search-coil testing and verification program was determining which combinations of search coils would form functional triplets with good quadrupole bucking. Dipole bucking is dependent upon matched coil areas, whereas quadrupole bucking is dependent also upon the relative positioning of coils within the triplet. Although the magnetic areas of the coils can be measured independently, the relative positions of the centroids of the coil bundles within the triplet are strongly dependent upon the assembly technique and mechanical measurements. To meet our quadrupole bucking specification, coil-bundle locations had to be accurate to within 25 μm. Search-coil areas were measured magnetically and calculated from the mechanical measurements. Coils whose magnetic and mechanical areas differed by more than 1/2 turn (~0.25%) were rewound.

Mechanical measurements were entered into a series of LOTUS 123 spreadsheets, which allowed convenient "what if" combining of coil triplets. Coil triplets with promising (area-dependent) dipole bucking ratios were physically combined, and their differences were measured magnetically. The resultant absolute magnetic areas (to within than 0.1%) and dipole bucking ratios were also entered into the LOTUS spreadsheet.

Coil combinations with good mechanical-magnetic measurement correlations had their mechanical dimensions entered into a FORTRAN search-coil simulation program. This program computes dipole and quadrupole bucking ratios and harmonic sensitivities for each search-coil triplet. Its output was reviewed, and a final go/no-go determination was made. This concluded the testing/verification phase of the search-coil array construction.

Magnetic Area Determination

We determined the area of each integral coil by measuring the change of flux-linkage as the coil was flipped in an Nuclear Magnetic Resonance (NMR) calibrated magnet. Equation 1 identifies the parameters used to determine coil area.

$$nA_i = \frac{\frac{1}{2}\Delta\psi_i}{\bar{B}_\perp} = \frac{\psi_{fs}\ (\frac{1}{2}\Delta E_i/E_{fs}}{\bar{B}_{nmr}} \qquad (1)$$

nA_i = turns-area product of coil i

$\Delta\psi_i$ = change in flux-linkage experienced when coil i is flipped in a magnetic field

ΔE_i = change in potential of an electronic integrator when the coil is flipped in a magnetic field; the flux standard is a means of calibrating the electronic integrator

ψ_{fs} = known flux-linkage generated by a flux standard

ΔE_{fs} = output potential of the electronic integrator when the flux standard is switched (from saturation of one polarity to saturation of the opposite polarity)

$\bar{B}_\perp = \bar{B}_{nmr}$ = average magnetic induction normal to the coil area as determined by mapping with a NMR magnetometer

Although we can determine the coils turns-area (nA_i) with an absolute accuracy of better than 0.1% (nA_i), we can determine the relative areas of three coils stacked coaxially and connected in series to greater accuracy. When connected in series opposition, the net turns-area ($\sum(nA_2 - [nA_1 + nA_3])$) of the three coils is close to zero. When this stack of coils is flipped, the change in integrator output is proportional to the difference in the net turns-area of the three coils.

By eliminating small inherent variations in magnetic induction and positioning uncertainties, we are able to determine area differences to better than 0.05% (nA_2), so we can predict dipole bucking ratios of over 2000.

Quadrupole Bucking-Ratio Predictions

Quadrupole search-coil sensitivity and bucking is dependent on the relative positions as well as on the areas of individual search-coil bundles within each triplet. As a final check on the suitability of promising triplet sets, we developed a FORTRAN program that, given the coil-bundle positions relative to the axis of revolution of the search-coil array, would calculate the dipole and quadrupole bucking ratios and the sensitivities of the search-coil array to higher harmonics. The pass-fail criterion for the 10-cm-long center-coil triplet was a quadrupole bucking ratio of 200; for the 70-cm-long sets used for the ends the bucking-ratio criterion was 100.

Test Results Summary

Tables I and II list calculated and measured bucking ratios.

TABLE I. CALCULATED DIPOLE BUCKING RATIOS.

	End A	Center	End B	Series
Mechanical measurement	1028	470	992	-
Magnetic measurement	1700	1425	1255	-
Program calculation	137	483	370	-

TABLE II. CALCULATED AND MEASURED QUADRUPOLE BUCKING RATIOS.

	End A	Center	End B	Series
Program calculation	362	1031	462	-
Short quad	116	280	275	-
Q-1A-1 @ 20 A	61	265	195	112
Q-1A-1 @ 7 kA	60	250	200	120
Q-1A-1 @ 3 kA	-	254	-	118

The measured quadrupole bucking ratios of the center and end-B coil sets are limited because the off-axis coils are not perfectly matched. As is shown by Fig. 3, the quadrupole content of the bucked coils was 90° out of phase from the fundamental. Figure 3 is a raw-data plot using the 10-cm-long central coil set for quadrupole Q-1A-1 at 20 A. The upper plot is the fundamental, whereas the lower plot was made with the coils in the bucked configuration.

Figure 4 is a semilog plot of error harmonic ratios for the same data set.

Accuracy

On the basis of an assembly tolerance of ±25 μm, we can measure the quadrupole strength to an accuracy of ±0.7%. The same assembly tolerance leads to a 0.6% error for the sextupole term, with the error rapidly decreasing for higher terms.

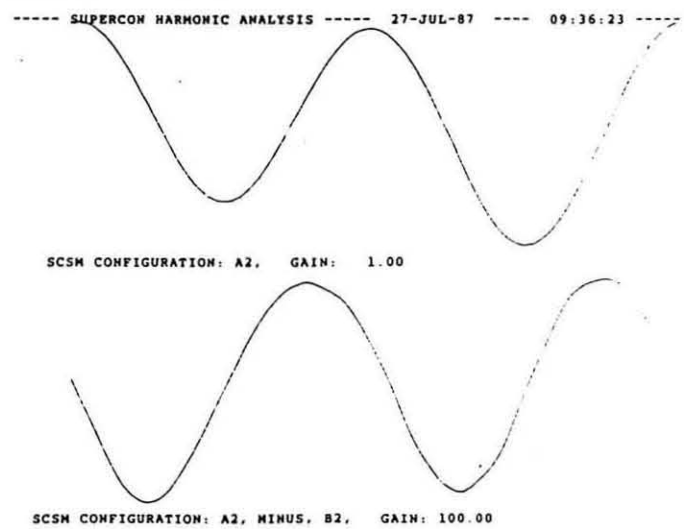

Figure 3. Raw-data plot of SSC model quadrupole Q-1A-1 at 20 A. The lower plot of the bucked coils shows that its quadrupole phase is 90° out of phase from the upper, unbucked, raw-data plot.

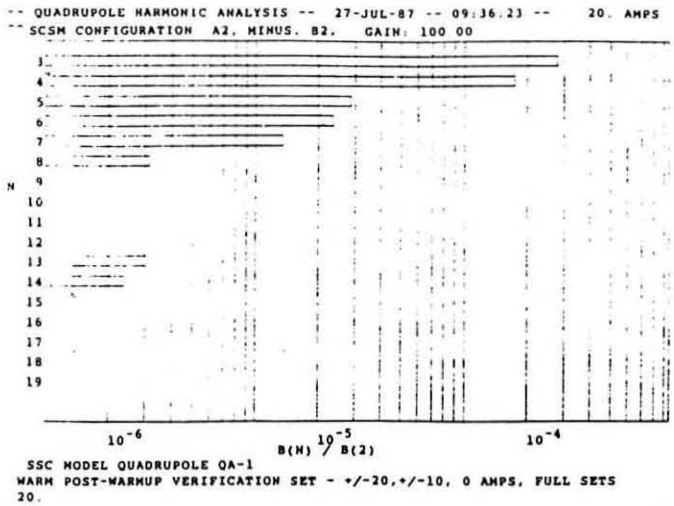

Figure 4. Semilog plot of error harmonic ratios of SSC model quadrupole Q-1A-1 at 20 A.

Discussion

The techniques used allowed us to obtain excellent bucking ratios for two out of the three coil triplets, without using resistive networks. Although the bucking ratio obtained for the end-A coil set is disappointing, it should be adequate for measuring SSC model quadrupoles. Further testing is planned with a short quadrupole to better determine the accuracy of this search-coil array.

Acknowledgements

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Reference

1. M.I. Green, P.J. Barale, W.S. Gilbert, W.V. Hassenzahl, D.H. Nelson, C.E. Taylor, N.J. Travis, and D.A. Van Dyke, "Magnetic Measurement System for Harmonic Analysis of LBL SSC Model Dipoles and Quadrupoles," Tenth International Conference on Magnet Technology, Boston, MA., Sept. 1987.